Research on a Lecture-Tutorial Approach to Teaching Introductory Astronomy for Non–Science Majors

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Abstract

The *Lecture-Tutorial* curriculum development project produced a set of 29 learner-centered classroom instructional materials for a large- enrollment introductory astronomy survey course for non-science majors. The Lecture-Tutorials are instructional materials intended for use by collaborative student learning groups, and are designed to be integrated into existing courses with conventional lectures. These instructional materials offer classroom-ready learner-centered activities that do not require any outside equipment or drastic course revision for implementation. Each 15-minute Lecture-Tutorial poses a sequence of conceptually challenging, Socratic dialogue-driven questions, along with graphs and data tables, all designed to encourage students to reason critically about difficult concepts in astronomy. The materials are based on research into student beliefs and reasoning difficulties, and use proven instructional strategies. The Lecture-Tutorials have been field- tested for effectiveness at various institutions, which represent a wide range of student populations and instructional settings. In addition to materials development, a second effort of this project focused on the assessment of changes in students' conceptual understanding and attitudes toward learning astronomy as a result of both lecture and the subsequent use of Lecture-Tutorials. Quantitative and qualitative assessments were completed using a precourse,

postlecture, and post-Lecture- Tutorial instrument, along with focus group interviews, respectively. Collectively, the evaluation data illustrate that conventional lectures alone helped students make statistically significant--yet unsatisfactory-- gains in understanding (with students scoring at only the 50% level postlecture). Further, the data illustrate that the use of Lecture- Tutorials helped students achieve statistically significant gains beyond those attained after lecture (with students scoring at the 70% level post-Lecture- Tutorial). Quantitative evaluation of student attitudes showed no significant gains over the semester, but students reported that they considered the Lecture-Tutorials to be one of the most valuable components of the course.

1. INTRODUCTION

Every year, more than 200,000 non–science major undergraduate students enroll in an introductory astronomy course (Fraknoi 2001). However, for many of these students, this course is not introductory at all; it is their terminal course in astronomy, and in fact marks the end of their formal education in science. Introductory astronomy therefore represents an opportunity to engender the excitement of scientific inquiry in students who have chosen to avoid science courses throughout their academic careers. These students reflect a wide cross-section of college students. As such, this course serves as a unique forum to highlight the intimate relationships between science, technology, and society, while also modeling effective instructional strategies for preservice teachers who enroll in these courses.

Decades of research on student learning in introductory science courses, including astronomy, have revealed that faculty routinely overestimate the level of conceptual understanding achieved in these classes. Whereas many faculty believe that students are learning to appreciate the broad landscape of an exciting new field, students are all too often struggling with unfamiliar vocabulary and the naïve ideas that they bring to the classroom, which combine to result in a lower level of understanding of fundamental concepts than faculty hope (Bailey & Slater 2003; McDermott & Redish 1999; Schneps 1989; Tobias 1990). An oft-cited explanation for this low student achievement is the excessive reliance by the faculty member on lecturing as an instructional mode. This form of instruction--a method that is effective only for a minority of students but includes those most likely to become faculty themselves--allows students to take passive roles in the classroom and often results in minimal cognitive engagement and low conceptual gains.

A rapidly growing number of faculty recognize that the teaching and learning of science must be treated as a complex problem that requires a scholarly approach if one is to be successful in achieving his or her course goals. Results from recent surveys of faculty attending college teaching workshops reveal that although many faculty realize that lecturing alone is insufficient to help all students learn, faculty are largely unaware of what other instructional approaches will benefit their students and still be practical to implement in their existing classrooms (Bailey, Jones, & Slater 2003). Faculty who study the teaching and learning of science generally recognize that learning in a large lecture setting can be improved substantially by moving learners from a passive role to a more active role (Bonwell & Eison 1991). Duncan (1999) eloquently argues that attention-grabbing demonstrations and adept use of multimedia are not enough; truly active learning requires students to do more than passively watch a presentation. Numerous examples of how active learning can help to promote conceptual understanding exist in the science education research literature. For example, Mazur (1996) developed "Peer Instruction," whereby physics students work together in learning teams to answer a series of "ConcepTest" questions during lecture; Green (2003) recently extended Mazur's work into the realm of astronomy teaching. Sokoloff & Thornton (1997) demonstrated that physics students showed significant improvement on conceptually

challenging questions after using lecture demonstration strategies that are *interactive* in that they require students to discuss and commit to predictions about what will happen during the demonstration. Mestre (1991) found that to actively engage students' thought processes, it is beneficial for students to take the active role in generating their own problems rather than having the instructor pose problems. At the University of Washington, McDermott (1991) and her colleagues showed that a tutorial-based instructional approach informed by research on student misconceptions can produce significant gains in student learning in physics (see also McDermott & Shaffer 1992). Francis, Adams, & Noonan (1998) found that the University of Washington tutorials helped students retain conceptual understanding for more than three years after completing a course.

If the documented successes of these alternative instructional strategies point to which teaching environments are most effective for promoting student learning, why are most faculty not employing these strategies? One part of the answer is likely limited time and resources. Many of these effective instructional innovations require substantial effort and commitment by the faculty members and the institutions. Most faculty at doctoral-granting research institutions necessarily devote significantly more time to their research than to instruction. Further, faculty often lack the pedagogical expertise to successfully implement these teaching strategies. Yet another challenge of implementation stems from a need for institutional commitment to provide appropriate space, ample equipment, and adequate teaching assistants for large enrollment courses.

What we identified at the beginning of this project is the need for instructional materials that faculty can easily incorporate into existing courses and that do not necessitate additional institutional support, nor require the faculty member to become a pedagogical expert. To this end, we have developed *Lecture-Tutorials for Introductory Astronomy* (Adams, Prather, & Slater 2005; see Note 1) in an effort to improve the effectiveness of the introductory astronomy survey course when implemented by faculty accustomed to using conventional lecture methods. The materials were targeted specifically to serve this sometimes skeptical and certainly busy audience by retaining some sense of the professor-centered instructional style that forms the basis of most university astronomy classrooms.

This article first describes the development and implementation of these learner-centered instructional materials intended to supplement conventional large lecture courses for the non–science major population. By learner centered, we mean "environments that pay careful attention to the knowledge, skills, attitudes, and beliefs that learners bring to the educational setting" (Bransford, Brown, & Cocking 1999, p. 133-134). The article goes on to describe the assessment results--which illustrate significant gains in student conceptual understanding as a result of the lecture and the Lecture-Tutorials--and the impact on student attitudes.

2. DESIGN OF THE LECTURE-TUTORIAL INSTRUCTIONAL MATERIALS

In this section, we first describe the theoretical framework that guided the development of the Lecture-Tutorials, followed by an accounting of how these materials are ideally implemented in a traditional classroom.

Earlier research that surveyed numerous course syllabi by Slater et al. (2001) identified the most common topic areas covered by introductory astronomy courses for non–science majors (hereafter referred to as ASTRO 101). These topic areas, in conjunction with previously identified naïve student beliefs and reasoning difficulties (see Bailey & Slater 2003 for an exhaustive review), served to focus and inform the creation of the Lecture-Tutorials. A list of titles for the Lecture-Tutorials divided by topic is provided in Figure 1.

Figure 1. Lecture-Tutorials by Topic.

Naked-Eye Astronomy

- Position
- Motion
- Seasonal Stars
- Solar vs. Sidereal Day
- Ecliptic
- Path of the Sun
- Star Charts

Moon Phases

- The Cause of Moon Phases
- Predicting Moon Phases

Nature of Light and Electromagnetic Spectrum

- Luminosity, Temperature, and Size
- Blackbody Radiation
- Types of Spectra
- Analyzing Spectra

Tools and Telescopes

- Telescopes and Earth's Atmosphere

Motions in the Solar System

- Observing Retrograde Motion
- Orbital Period and Orbital Distance

The Solar System

- Earth's Changing Surface
- Temperature and Formation of Our Solar System

Our Sun

- Sun Size

Stellar Magnitudes

- Apparent and Absolute Magnitudes of Stars

Techniques in Astronomy

- The Parsec
- Parallax and Distance

Stellar Spectral Classification

- H-R Diagram
- Spectroscopic Parallax

Stellar Evolution

- Star Formation and Lifetimes
- Stellar Evolution

Characteristics of the Milky Way

- Milky Way Scales

Cosmology and the Big Bang

- Looking at Distant Objects
- Expansion of the Universe

In each Lecture-Tutorial, we endeavored to challenge known student difficulties with carefully designed tasks that focus on having students engage at a cognitively appropriately level to ensure that they confront naïve ideas. The Lecture-Tutorials are designed around a Socratic questioning approach that makes use of students' natural language to promote small cognitive steps with the goal of achieving a more scientifically accurate and sophisticated understanding. Astronomy spans a wide array of topics, and we know that student knowledge of these topics is structured in many different ways, which may include mental models (Redish 1994), ontological categories (Chi 1992), and "knowledge in pieces" (often referred to as *phenomenological primitives*; di Sessa 1988, 1993). The questions are written in a sequence intended to guide students' conceptual development. The activities are two to four pages long, and are often accompanied by data tables, graphs, or diagrams for students to interpret. Initially, students are asked to examine a novel situation that requires them to reflect on information that they have just heard in lecture. Students provide written responses and explanations to conceptually challenging questions, and are repeatedly asked to record answers on diagrams and graphs. One technique that we use to help students confront and resolve conceptual and reasoning difficulties is to present the text of a hypothetical "student debate" modeled after work by McDermott & Shaffer (1998). The students are directed to critically review the "student debate," which expresses common naïve ideas in the student's natural

language. They are then asked to make explicit whether they agree or disagree with each of the hypothetical "student statements," and provide an explanation of their reasoning. From a pedagogical perspective, challenging students to confront their own misconceptions is part of the process of cognitive conflict, which helps mediate meaningful and lasting conceptual change (Posner et al. 1982).

Our intent was to create a learner-centered instructional approach that could be integrated into existing courses without requiring faculty to give up lecture control wholesale. Lecture-Tutorials were designed to be used in large fixed-seat theater-style lecture halls with a single professor and no additional classroom facilitators. This is very different from the 20-to-30-student breakout/recitation section for which many research-based tutorial materials have been developed in introductory physics, and this imposed some strong limitations on our design. Unlike a more typical recitation environment in which student learning is strongly connected to conversations with trained teaching assistants, we needed to ensure that the majority of student difficulties could be resolved without significant help from the instructor. The cognitive steps are therefore small, and there are a number of built-in self-checks to encourage students to reflect on their developing ideas. Lecture-Tutorials promote the intellectual engagement of students in this challenging instructional setting by having students work collaboratively in pairs to capitalize on the benefits of social interactions.

Implementing the Lecture-Tutorials ideally consists of three steps. The first step is to pose a set of conceptually challenging questions presented to students at the end of an abbreviated lecture on a given topic to elicit and challenge students' fundamental understanding. If an unsatisfactory percentage of students are able to correctly answer the questions, this suggests that the accompanying Lecture-Tutorial should be used. What will be surprising to most faculty is that, even after conventional instruction, many students still provide incorrect responses to questions that appear simple to both students and faculty (Mazur 1996). Further, upon first inspection of the Lecture-Tutorials, faculty often believe that the difficulty level of questions is insufficient to intellectually challenge their students. However, our experience in field-testing and conducting faculty workshops indicates that both students and faculty find the Lecture-Tutorials to be conceptually challenging.

The second step, and most central to the core of this project, is to use one of the 15-minute collaborative-learning Lecture-Tutorials in the lecture classroom. During this time, the instructor changes roles--from lecturer to facilitator--and circulates among the student groups, interacting with students, posing guiding questions when needed, and keeping students on task.

The final step of each Lecture-Tutorial is to debrief the content covered and to bring closure for the students by eliciting student questions and comments. Another common debriefing approach is to make explicit the reasoning needed to fully understand the concepts and provide students with accurate language to describe the phenomenon under investigation. This is an important metacognitive step for both the students and the instructor in that it provides useful insight into how the Lecture-Tutorial experience has impacted student understanding.

3. RESEARCH DESIGN

Two overarching research questions guided the evaluation of the Lecture-Tutorials:

1. What is the effectiveness of a conventional lecture on student understanding?
2. What is the effectiveness of the Lecture-Tutorials on student understanding and their influence on student attitudes?

This study used a mixed-methods (Creswell 2002) one-group multiple measures research design (Freed, Ryan, & Hess 1991). The primary data source was students enrolled in ASTRO 101 for non–science majors at a large Research Level-1 doctoral-granting institution in the Southwest.

Data were collected precourse, postlecture, and post-Lecture-Tutorial using a 68-item conceptual inventory. This instrument used multiple-choice items over a specific range of topics selected to match those commonly taught in an introductory course (Slater et al. 2001). The majority of questions on the survey were written by the authors to broadly sample the dominant naïve ideas that students bring to the ASTRO 101 course. In addition, some items were culled from previously published evaluation instruments, including the Astronomy Diagnostic Test (Hufnagel et al. 2000), the Lunar Phases Concept Inventory (Lindell 2001), the Project STAR evaluation instruments (Sadler, 1992), and others (Slater, Carpenter, & Safko 1996). The important characteristic of the multiple-choice questions we created or selected was that they use attractive distractors based on commonly documented student misconceptions in astronomy (Bailey & Slater 2003; Comins 2001; Sadler 1998), or on phenomenological primitives (di Sessa 1993; Prather, Slater, & Offerdahl 2002). The overarching goal was to create an inventory that probed conceptual understanding rather than elicit only factual recall--in other words, a test that the students would rate as conceptually challenging. We endeavored to construct items in the natural language of students so as to test concepts rather than astronomy jargon. It is not always possible to accomplish this goal, which poses problems when the inventory is to be used prior to instruction. A few of the items do rely on some understanding of content-specific vocabulary in order for students to answer them correctly. Normally, questions using such technical vocabulary rather than natural student language are inappropriate for an inventory conducted precourse. However, because the majority of scores on individual questions do not cluster around 25% correct, it seems unlikely that the students are guessing randomly. In other words, it appears that students do have particular and consistent reasons for answering the questions the way that they do, suggesting that the technical language is not completely unfamiliar. Three professional research astronomers who have teaching experience with the target population evaluated each item on a preliminary version of the inventory to suggest content validity, and we retained only those items that all evaluators agreed were appropriate.

For the precourse data, the conceptual inventory was administered on the first day of class using Scantron forms. We split the inventory into two equivalent forms, with half of the questions on each form. The division of the questions on two test forms was done to reduce the survey administration time to about 15 minutes. This is important to avoid infringing on the inventory's construct validity (i.e., how well the measurement tests the theory). Validity can be threatened if it takes too long for students to complete the questions because they may cease to respond thoughtfully to items near the end.

To collect the postlecture and post-Lecture-Tutorial data, students responded to a subset of two or three closely related multiple-choice items selected from the original 68-item conceptual inventory. This subset of questions was chosen to align with the day's lecture topics and was administered immediately following lecture. The same subset of questions was asked again later, after students had completed the corresponding Lecture-Tutorial. (These post-Lecture-Tutorial data were often collected on a different

day.) This approach to data collection was relatively straightforward in design, albeit highly complex to carry out in the day-to-day context of a large enrollment course. It was necessary to distribute new Scantron forms to every student at the start of each class meeting. Because of the highly varying student attendance and requirements for anonymity surrounding human subjects research, we chose to aggregate all student results and use unpaired pre-post data.

It is worth noting that lectures were delivered by the first two authors and characterized by the research team as following the best practices of effective lectures, including the use of demonstrations, animations, and Microsoft PowerPoint, as described in Slater & Adams (2003). The lecturers have consistently received evaluation scores well above their departmental average on formal faculty course evaluations by students, and were identified as being notably enthusiastic and knowledgeable. What is critical here is that the authors maintained an instructor-centered classroom environment throughout this portion of the study.

A pre-post-course Likert-scale attitude survey was also administered. This survey (Zeilik n.d.) provided a list of 34 statements about which students were asked to indicate their level of agreement on a scale varying from 1 (*strongly disagree*) to 5 (*strongly agree*). In addition, an end-of-the-course qualitative study was performed to determine student impressions and beliefs about their learning using the Lecture-Tutorials. This study involved conducting a whole-class focus-group interview, which was carried out by the University Teaching Effectiveness Center. We also reviewed the formal end-of-course evaluations submitted by students.

4. RESEARCH RESULTS

Our first research question examined the effectiveness of a conventional lecture on student understanding of the main topics taught in ASTRO 101. Based on the rhetoric of the ineffectiveness of instructor-centered lectures, we had anticipated that there would be only modest gains in student scores from precourse to postlecture. The average score on the 68-item conceptual inventory administered precourse was 30% correct, whereas the postlecture average score was 52% correct (see Note 2). Although this 20% gain in average score demonstrates a statistically significant increase in scores (alpha < .05) and could be considered to be a great success for lecture-centered instruction, we are wholly unsatisfied when our students are only able to answer half of these conceptual questions correctly after targeted instruction. To illustrate the types of questions used and their corresponding precourse and postlecture results, several of the items and corresponding scores are provided in Figure 2. These results serve as evidence that lecture-centered classroom environments, even those demonstrating best lecture practices, are largely ineffective at promoting meaningful and compelling conceptual gains on traditional astronomy topics presented to non–science majors.

Figure 2. Sample of Conceptual Survey Items and Results.

The diagram below shows Earth and the Sun, as well as five different possible positions for the Moon. Which position of the Moon best corresponds with the phase of the Moon shown at the right in the figure?

FIG_fig2.1

The graph below shows the blackbody spectra for three different stars. Which of the stars is at the highest temperature?

a) Star A
b) Star B
c) Star C

FIG_fig2.2

If our universe is expanding, what are the implications for the separation between two stars within our galaxy?

a) The two stars are moving farther apart.
b) The two stars are moving closer together.
c) The two stars are remaining approximately the same distance apart.

You observe a star rising directly to the east. When this star reaches its highest position above the horizon, where will it be?

a) High in the northern sky
b) High in the eastern sky
c) High in the southern sky
d) High in the western sky
e) Directly overhead

Precourse (*N* = 42)   2%

Postlecture (*N* = 135)   19%

Post-Lecture-Tutorial   66%

The stars Antares and Mimosa each have an absolute magnitude of -4.6. Antares is spectral type M and Mimosa is spectral type B. Which star is larger?

a) Antares.
b) Mimosa.
c) They are the same size.
d) There is insufficient information to determine this.

Precourse (*N* = 39)   26%

Postlecture (*N* = 94)   37%

Post-Lecture-Tutorial   72%

Note: Although faculty sometimes question the potential ambiguous nature of the first question presented here, students do not. In all cases, students are told to assume that they are working from their location in the northern hemisphere unless otherwise noted. Materials have not yet been adapted for the southern hemisphere to the best of the authors' knowledge.

The second research question focused on student cognitive and affective gains resulting from the use of Lecture-Tutorials. Although students were able to provide correct responses to about half of the items after lecture, we were not sure how much improvement in scores would result from only investing an additional 15 minutes in learner-centered instruction by doing the Lecture-Tutorials. We found that students made statistically significant gains on the 68-item conceptual inventory beyond those achieved postlecture. The mean percentage correct score increased from 52% immediately following lecture to 72% after completing the Lecture-Tutorials. This additional 20% gain made by students, above the initial 20% gain achieved after lecture, is considered quite high given the small amount of class time invested. It is also a noteworthy gain because we believe that student gain scores are nonlinear, such that an increase from 50% to 70% correct is much more challenging to achieve, for both instructors and students, than the prior increase from 30% to 50%. Because of the conceptual difficulty and attractive nature of the distracters used in the questions, we do not believe that this dramatic increase is simply a result of students memorizing the answers or due to them having seen the questions as a pretest.

The mean scores on the Likert-scale attitude survey were nearly identical precourse to postcourse. In almost every individual item, students showed no statistically significant gain. These results are consistent with other studies using the same instrument (viz., Zeilik & Bisard 2000) and lend support to the idea that student attitudes are particularly difficult to impact even when conceptual knowledge increases.

In contrast, the results from the whole-class focus-group interviews conducted by an external evaluation team clearly indicate that many students thoroughly enjoyed the course because it was designed around the Lecture-Tutorials. To our surprise, several students stated that it was one of the most important parts of the class. Representative comments include:

- "We are able to discuss topics with other students and therefore, we help each other!"
- "Why don't all professors use tutorials during class?"

On the end-of-course evaluations, students frequently commented positively on the Lecture-Tutorials without being prompted. Comments were consistent with those from the focus groups, and include:

- "I really like the way this class is taught. The lectures, which are followed by reinforcing Lecture-Tutorials, make the information so clear to me."
- "I liked the Lecture-Tutorials, they were very helpful. I am not a science person, but I feel I learned a lot!"

From these collective results, we conclude that implementing Lecture-Tutorials in this setting, which reduced the amount of time available for lecturing by approximately 15 minutes per class period, made dramatic and significant positive impacts on students' understanding of astronomy. In addition, many students reported that the Lecture-Tutorials contributed positively to their learning and enjoyment of the course.

5. CONCLUSIONS

Research on how students learn science repeatedly shows that the largest learning gains result *when students are active participants in the learning process* (e.g., Wandersee, Mintzes, & Novak 1994). However, providing students with opportunities to be active learners is a formidable challenge in the context of large-enrollment lecture-based science survey courses for undergraduate non–science majors. Recognizing that most scientists who teach ASTRO 101 will not completely abandon lecture as the dominant classroom instructional approach, the philosophy of this project was to develop a suite of activities that would positively impact students' understanding through active engagement techniques that can be integrated into a lecture-based course without the need for significant faculty professional development.

These notions on how instructional methods influence student learning are confirmed by our results. From the precourse and postlecture responses we find that, even after conventional lectures, student cognitive gains, although statistically significant, are still below our desired expectations, where average postlecture scores were only 52%. However, creating a rich environment for students to engage in learner-centered instruction, albeit only for brief periods, promotes significant increases in conceptual understanding (beyond those achieved postlecture), as shown by the post-Lecture-Tutorial results where student scores increased to 72%.

From the overwhelmingly positive responses on our workshop evaluation forms, we infer that the Lecture-Tutorials project is fulfilling an important need within the astronomy teaching community. Our evaluations tell us that many college faculty feel constrained to use the lecture-based methods that they experienced as students, even though they are aware that innovative approaches exist that would likely further increase student understanding (Bailey et al. 2003). Many of these faculty stated that the

instructional materials developed as part of this project have enabled them to take a major step toward implementing learner-centered instructional strategies in their classrooms.

NOTES

Note 1: The initial dissemination of this project was supported by NSF DUE CCLI 9952232. As a result of strong encouragement from the National Science Founcation (NSF), Prentice Hall was contracted to disseminate these materials through commercial publication (currently under ISBN 0-13-147997-0). Prentice Hall had proved to be very successful in disseminating *Tutorials in Introductory Physics* (McDermott & Shaffer 1998), and we wished to leverage their existing infrastructure. The publisher supports a Web site (http://www.prenhall.com/tiponline) that includes a detailed instructor's guide. College teaching workshops on implementing the materials are being offered at professional conferences such as those of the American Association of Physics Teachers, the American Astronomical Society, the American Geophysical Union, and the Astronomical Society of the Pacific through the support of the NASA JPL Navigator and NASA Spitzer EPO programs. Summer faculty workshops are also being offered through the NSF Chautauqua program.

Note 2: Because of the nature of the data collection in this study, there is no single *n* that can be reported for these data. For the pretest, two forms were administered; 39 students responded to Form A, and 42 students responded to Form B. Approximately 40 more students completed the Astronomy Diagnostic Test at the same time. The number of students who responded postlecture and post-Lecture-Tutorial is approximately 100, although the number varied from day to day with attendance. To calculate the values reported, we first determined the number of students who got each question correct. We then averaged these numbers to calculate a total score for the 68-item concept inventory for each of the three administration times (precourse, postlecture, and post-Lecture-Tutorial). We do not report the standard deviations because it is difficult to appropriately interpret these numbers. However, the results are consistent with other results from this project.

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